Results from Automated Cloud and Dust Devil Detection Onboard the MER Rovers

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Abstract

We describe a new capability to automatically detect dust devils and clouds in imagery onboard rovers, enabling downlink of just the images with the targets or only portions of the images containing the targets. Previously, the MER rovers conducted campaigns to image dust devils and clouds by commanding a set of images be collected at fixed times and downloading the entire image set. By increasing the efficiency of the campaigns, more campaigns can be executed.

Software for these new capabilities was developed, tested, integrated, uploaded, and operationally checked out on both rovers as part of the R9.2 software upgrade. In April 2007 on Sol 1147 a dust devil was automatically detected onboard the Spirit rover for the first time.

We discuss the operational usage of the capability and present initial dust devil results showing how this preliminary application has demonstrated the feasibility and potential benefits of the approach.

1. Introduction

Dynamic atmospheric phenomena observed by the Mars Exploration Rovers (MER) include dust devils and clouds. These scientifically interesting events are typically rare, especially when out of season. Traditionally, dust devil and cloud campaigns on MER have been conducted by collecting a set of images at a fixed time pre-specified in the command sequence and then downloading the full image set. In general, these events are relatively rare; thus in most seasons, few images contain the target events of interest. Further, downlink bandwidth is often quite limited due, among other factors, to limited power and downlink windows. To provide an opportunity for scientists to obtain data on more of the targeted events, we have developed and deployed a new approach on the rovers. In this approach, images collected during a campaign are analyzed onboard to identify the presence of science features of interest (i.e. dust devils and clouds), providing a screening mechanism. By employing this screening approach, many images can be collected onboard resulting in a much greater time range for capturing the rare phenomena. Even when the images cannot be down-linked (such as when too many events are detected), compact summary statistics on the number and type of events can be still be down-linked to provide valuable information.

The code implementing these algorithms has been integrated with the MER flight software and uploaded to the MER rovers as part of the R9.2 software upgrade. Both the dust devil and cloud algorithms have successfully run on the MER rovers, have successfully passed initial checkouts, and are approved for routine operational usage.

In this paper, we briefly outline our algorithmic approach to detecting clouds and dust devils onboard. We then describe the operational usage scenarios. We present initial results on the performance of the dust devil algorithm providing quantification of potential benefits. This is followed by a discussion of lessons learned and plans for future improvements and extensions as well as related work before concluding.

2. Dust Devil Detection

A dust devil is a localized atmospheric phenomena consisting of a whirling updraft or vortex. Dust devils on Mars are of interest both for scientific and engineering reasons. Dust devils are thought to have cleared the MER rover solar panels of dust increasing the power available to the rovers. Martian dust devils are considered one of the key mechanisms for transporting dust from the surface into the atmosphere at Mars. Physical parameters of interest include size, spatial distribution and motion, frequency of occurrence, particle size and density.

Dust devils were detected in Mars Pathfinder imagery by comparing spectral bands [1, 2]. For this application, we chose to identify the dust devils using motion detection in a temporal sequence as it is applicable to grayscale imagery. While in theory, detecting rapid motion in a scene is not equivalent to detecting dust devils, in practice changes in a sequence of fixed scene images taken over a short period of time on Mars will be predominantly from dust devils. Dust devils are high dust opacity features on a dusty background and often have a faint signature in an image. The main challenge is to detect these often subtle features in the presence of significant image noise. The algorithm implemented consists of a preprocessing step to reduce image noise followed by an image averaging. The difference between the average image and the input or test image is then computed. Noise effects are removed from the difference image and blob detection is performed on the remaining differences. A buffered bounding box is constructed around each detection to ensure the full dust devil is captured. For further details on the algorithms as well as ground-based experimental testing results, see [3, 4].

3. Cloud Detection

Although the Martian atmosphere has very limited amounts of water vapor, the temperature, pressure, and atmospheric dust are such that the atmosphere can produce clouds. However, clouds on Mars are not as pronounced as clouds on Earth. Clouds on Mars may be localized or may cover extended regions, but are most commonly observed in the equatorial latitudes [5, 6]. More study is needed to understand the behavior and role of clouds in the Martian atmosphere.

The approach to detecting clouds, in contrast to dust devil detection, is to analyze individual images. One of the motivations for this is that the time frame over which the clouds may change significantly is too long to require the rover to remain motionless on a regular basis, as would be necessary for effective application of image differencing. We assume that significant intensity variations in the sky in the image correspond to clouds. Our approach to automating the detection of clouds is to first locate the sky (equivalently, the horizon) in an image and then determine if there are high variance regions in the sky. While we will not be discussing operational cloud detection results in this paper, the algorithm, achieved over 93% accuracy in testing on 210 hand-labeled images taken by the Mars Exploration Rover Opportunity. For more details on the algorithm and experimental testing see [3, 4].

4. Upload and Deployment

The dust devil and cloud detection algorithms were integrated with the MER flight software and uploaded to the MER rovers in the summer of 2006 as part of the R9.2 software upgrade. The MER cloud and dust devil detection capability is implemented by a primary command called WATCH and a set of supporting commands. The WATCH command itself triggers algorithm execution and sets various bounds for resource usage (e.g. total runtime, maximum images to save, maximum megabits to save, etc.). When any of these resource limits are exceeded WATCH terminates its run. Supporting commands set memory usage, various algorithm parameters (including whether to search for clouds or dust devils), and whether or not to enable image masking to allow for better compression and save on downlink bandwidth. All commands required for a single detection run are grouped into sequences for convenient reuse. For current nominal operations, there are two WATCH sequences, one used to search for clouds and another used to search for dust devils.

The nominal surface runtime for a cloud WATCH sequence is two minutes on the 20 MHz RAD6000 rover processors. Up to one minute is required to acquire a left Navcam image and save it to a MER image buffer. Another 30–60 seconds is required to analyze the image on the rover. WATCH analyzes the Navcam image, first separating sky from ground by searching for a horizon line. Next it looks for regions of high-variance within the sky. If such regions are found, a bounding-box around the region of interest is saved in the WATCH summary telemetry and the image itself is saved, both for later downlink.

The nominal surface runtime for a dust devil WATCH sequence is one hour. Unlike the one-off cloud detection, dust devil detection can run for as long as the rover is able to remain stationary and has sufficient power to acquire and analyze images. For dust devil detection, WATCH has two different image acquisition strategies. In the first, a single image buffer is used to acquire Navcam images. Since dust devil detection relies on image differencing to detect motion, at least two images must be acquired before image analysis can start. When only a single image buffer is used, the time between successive frames can be up to two minutes, as it takes one minute to acquire the image and one more to perform frame-to-frame analysis and search for differences between images. The second image acquisition strategy makes use of additional MER image buffers (up to 10) to rapidly (one minute spacing) acquire a series of images and then analyze the series in batch. While both acquisition strategies have been tested on the surface, the single image buffer mode is currently more common. As with WATCH cloud, when regions of interest are found, a bounding-box is recorded in telemetry and the image containing the regions is saved for later downlink.

A primary benefit of WATCH is its ability to operate unattended for long durations, searching for (rare) image features of interest, and saving only images that contain such features. WATCH offers an additional bandwidth-saving capability in the form of image masking. When masking is enabled, before an image is saved, all pixels outside the region of interest bounding boxes are filled (overwritten) with a single value (typically gray). This leads to large homogenous regions in the saved image, which compress well (using ICER compression [7, 8]) for downlink. In operations, image masking is combined with an acquisition of full frame baseline image immediately before WATCH is run. This baseline image can be used as a backdrop upon which to overlay the detected dust devils once they have been extracted from the masked image. WATCH can, in theory, save significant bandwidth over the more traditional method of acquiring as many images in succession as available FLASH space and downlink bandwidth allow. We discuss results and the use in practice in the next two sections.

5. Initial Dust Devil Results

The WATCH command has been fully checked out operationally and WATCH dust devil image sequences have now been taken on 26 separate sols. Of these sols, an event was detected on 21 sols. This appears to represent a savings of 20% if no images were downloaded when there were no detections. At the image level, 393 images were collected during the 26 WATCH dust devil sequences. Of these 393, there were detections in 120 images. Thus, only 30% of collected images need be returned, representing a significant potential bandwidth savings.

Within the 120 images, 533 candidate features were identified. A breakdown of the nature of these detections is shown in Table 1. Examples of several classes of detections are shown in Figure 1. Most commonly true dust devils are detected on the horizon, as shown in Figure 1. Due to the extensive atmospheric dust, these are often not obvious to the human eye without stretching the image contrast. Dust devils have also been observed against the surface, as in Figure 1. This most commonly occurs when the rover is on an incline or hill and is observing into the valley below.

While dust devils are the most common true region of interest, WATCH has also detected thin, short-lived bright streaks in several images. These streaks are believed to be galactic cosmic rays. WATCH identifies this brief appearance in one image of a sequence and disappearance in the next image.

A fourth type of region commonly identified as a feature is a ground region consisting of soil and rocks within approximately 20m of the rover. This, in fact is the most common detection, with multiple such features often being detected in a single image. During development, the algorithm was tuned to minimize the risk of missing candidate dust devils at the potential risk of increased false alarms and this is a side effect. It should be emphasized, however, that the current algorithm, as implemented, achieved a 70% reduction in the number of images to be transmitted. The use of auxiliary information on the distance of the detection from the rover could eliminate this class of feature that cannot be dust devil detections. Such an option would be a preferable to reducing the sensitivity of the algorithm, due to the desire to not miss any true dust devils. This is a candidate for future improvements of the algorithm.

The final class of identification was in images in which the camera was pointed at the sky and there was no horizon. In this case, the algorithm was instructed to flag the image, thus it marks the entire image as a region.

Table 1. Classification of candidate features identified.

Classification of Detection	Percent of detections
Candidate dust devil on horizon	18
Candidate mid-range dust devil	3
Cosmic ray	1
Surface within ~20m of rover	76
Sky	2

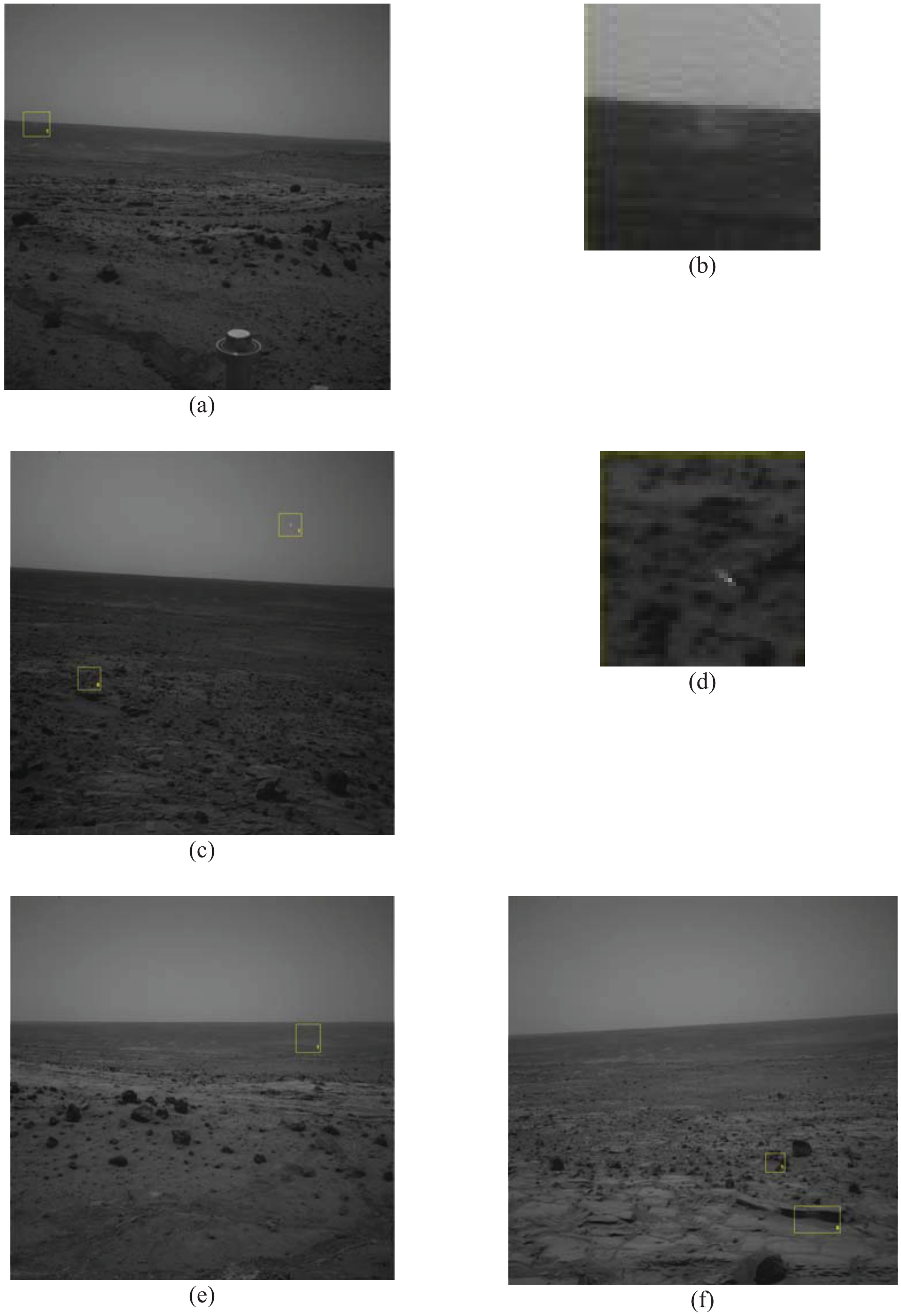

Figure 1. Classes of detections identified by the dust devil detector on the Spirit rover. (a) dust devil (b) zoomed in and gray-scale stretched dust devil (c) cosmic ray detections (d) close-up of cosmic ray effect in image (e) mid-range false-alarm detection (f) foreground false-alarm detections.

6. Future Extensions

We discuss both plans for improving the WATCH command itself beyond those mentioned in Section 5, as well as plans for further extensions of onboard science capabilities.

6.1. Future WATCH Considerations

Prior to the design and implementation of WATCH, the MER operations team had developed other sequences for acquiring cloud and dust devil images. Unlike WATCH, none of these sequences operates autonomously.

The standard MER cloud sequence points the Navcam above the horizon so the image contains only sky. A 4×1 Navcam mosaic (with changing azimuths) is then acquired and each of the four frames are downsampled from their original 1024×1024 pixel size to 512×512 pixels. A single cloud sequence takes approximately four minutes of surface runtime. Since the initial WATCH command was not designed with an image downsampling capability, each WATCH image consumes as much space at the 4 image mini-Navcam mosaic taken with the previous method. While we do not yet have an operational assessment of the results of the performance of WATCH for cloud detection, it can be seen that in current operations WATCH provides a benefit if less than a quarter of the images have clouds. In the future, we would like to add the downsampling capability to the WATCH functionality.

The standard MER dust devil movie sequence points the Navcam at the horizon and subframes (crops) each acquired image to quarter height (1024×256). Subframing allows four dust devil movie frames to be acquired for the same number of bits as a single full image. While WATCH does not currently operate on subframed images it does have the capability to mask areas of interested followed by image compression providing potentially significant bandwidth savings. This capability has yet to be fully explored to assess the practical bandwidth savings. In the future, the subframing capability will be desirable. This would have the additional benefit of eliminating nearly all of the near-field false alarms observed in the results in Section 5.

In contrast to the standard MER dust devil movie sequent, WATCH can selectively save only frames of interest. Selective frame saving enables WATCH to operate for long stretches of time while consuming far less bandwidth, when no dust devils are present, than a standard movie sequence.

6.2. Future Applications

The WATCH capability involves a form of data prioritization in which only the images with events of scientific interest need be downloaded. In the future, we would like to be able to expand the prioritization capabilities as well as enabling more active forms of opportunistic science. While advanced autonomous science systems are under development (see next section), we are currently working to integrate elements into the rover flight software. There is an activity under way to enable the rovers to perform automated science target selection which would permit targeted remote sensing with limited field of view instruments such as the mini-TES on MER or the ChemCam instrument on the Mars Science Laboratory rover during or after a traverse. Currently, targets are manually selected by the science team based on previously downloaded imagery while end of sol activities are untargeted or collected based on pre-specified coordinates that are not a function of the scene.

While we have focused on Mars rover applications, onboard science capability can benefit a number of missions, particularly when downlink bandwidth is limited relative to data collection capabilities. One area that we have been studying is a flagship mission to Titan with an airship and possibly an orbiter. In this case, it may be difficult if not impossible to return to a region so identification of interesting features onboard and possibly collecting additional data could significantly increase the science return and the chances of characterizing rare or spatially limited features.

7. Related Work

There are several systems that have demonstrated onboard science data analysis for rovers in testbeds and field testing. The Onboard Autonomous Science Investigation System (OASIS) system has been developed to evaluate, and autonomously act upon, science data gathered by in-situ spacecraft such as planetary landers and rovers [9, 10]. Prototype versions of the dust devil and cloud detection algorithms of the dust devil and cloud detection algorithms were initially developed for the OASIS system. These prototype algorithms were refined to achieve the required accuracy in the onboard environment of the MER rovers, integrated into the flight software, and thoroughly tested under a dedicated MER infusion activity.

Wagner, et al [11] and Pedersen [12] describe a system that was successful at autonomously identifying meteorites in Antarctica. Gulick, et al. [13] described techniques for analyzing field test data for the Marsokhod rover. This work also pioneered horizon detection for sky removal. Gilmore, et al., [14] presented several methods developed specifically for autonomous rover science. Roush, et al., [15] presented a system for science inference on a rover [15].

There has also been significant development of methods for autonomous science including classification of features and survey in association with the automated identification of life in the Atacama Desert [16, 17, and 18].

The Autonomous Sciencecraft (ASE) uses autonomy software which has been flying on the Earth Observer-1 (EO-1) satellite since the fall of 2003 [19]. This new technology facilitates autonomous science-driven capabilities. Among the ASE flight software is a set of onboard science algorithms designed for autonomous data processing, to identify observed science events [20].

The rovers have autonomous capabilities that have been employed extensively over the course of the mission. GESTALT, an automated stereo-based hazard avoidance program steers the rovers away from rocks and steep hills, or can keep track of its position using on-board visual odometry, more accurate than wheel odometry which is affected by slippage [21]. In this paper, we have presented an application that moves onboard automation from the strictly engineering domain to the science domain.

8. Conclusions

We have given an overview of a new capability on the MER rovers for identifying dust devils and clouds onboard. Preliminary dust devil detection results indicate significant potential for increasing the number of events identified and downlinked for science analysis in selected usage modes. Early operational usage has also led to an understanding of aspects in which the applications could be made even more beneficial to the science team. This preliminary application has demonstrated the feasibility and potential benefits of onboard analysis and opens a new operational paradigm as a viable option.

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